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Comparison of High Temperature, High Frequency Core Loss and Dynamic B-H Loops of Two 50 Ni-Fe Crystalline Alloys and an Iron-Based Amorphous Alloy

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ABSTRACT

The availability of experimental data that characterizes the performance of soft magnetic materials for the combined conditions of high temperature and high frequency is almost non-existent. An experimental investigation was conducted over the temperature range of 23 to 300 C and frequency range of 1 to 50 kHz to determine the effects of temperature and frequency on the core loss and dynamic B-H loops of three different soft magnetic materials; an oriented-grain 50Ni-50Fe alloy, a nonoriented-grain 50Ni-50Fe alloy, and an iron-based amorphous material (Metglas 2605SC). A comparison of these materials shows that the nonoriented-grain 50Ni-50Fe alloy tends to have either the lowest or next lowest core loss for all temperatures and frequencies investigated.

INTRODUCTION

Power electronic components for future high power space systems will most likely be exposed to harsh environments and will need to meet the requirements of high efficiency, low specific mass, high reliability and long life. Low system mass can be achieved by operating the power electronics at high temperature to reduce its cooling radiator mass and, also, by operating the power magnetics and capacitors at high frequency to reduce their mass.

Presently, the experimental data available to the designer on the electrical and magnetic characteristics of soft magnetic materials is almost limited to room temperature data taken under DC or 60 Hz conditions. The NASA-Lewis Research Center has initiated an experimental program to characterize soft magnetic materials over the temperature (T) range of 23 to 300 C and frequency (f) range of 0.1 to 50 kHz for both sinusoidal and non-sinusoidal voltage excitation [1]. Previous papers have given and compared the experimental results obtained for an 80Ni-Fe crystalline alloy and two iron-based amorphous materials for T of 23 to 300 C and f of 1 to 50 kHz [2,3].

The experimental results presented in this paper are for the oriented-grain (OG) and nonoriented-grain (NOG) 50Ni-50Fe crystalline alloys. One of the amorphous materials previously reported, Metglas 2605SC, is included for comparison because it has a saturation flux density similar to the 50Ni-50Fe alloys. The experimental results reported here greatly extend the core loss and dynamic B-H loop data base for these materials. Experimental investigations of the two 50Ni-50Fe alloys reported here were also made during the late fifties [4,5,6] and late sixties [7,8]. Although those investigations included tests up to 500 C, they were done primarily under DC conditions with 3.2 kHz being the highest f reported at 250 C.

MATERIALS AND EXPERIMENT DESCRIPTION

Table 1 gives a comparison of some of the pertinent magnetic, electrical, thermal and physical properties of the two 50Ni-50Fe alloys and the Metglas 2605SC amorphous material.

Each material was tested separately using three cores for each test. The test cores were toroids wound from 0.001 inch thick by 0.25 inch wide tape with OD = 1.25 inches and ID = 1.0 inches. By Faraday's Law, the maximum flux density (B_m) was calculated as the ratio of flux to core magnetic cross-sectional area (A_c). A_c is calculated from $A_c = (M/D\bar{\ell}_m)$, where M, the mass of the core, is measured with an analytical balance, D is the magnetic material's physical density, and $\bar{\ell}_m$ is the mean path length of the core determined from OD and ID. A description of the makeup of the test cores is given in Reference 2 along with a description of the instrumentation, and the equations and procedures used to obtain the test results. Every effort was made to prevent local heating of the test core by capturing the required induced voltage and exciting current waveforms in the minimum length of time. From these waveforms, the specific core loss (SCL), which is the core loss normalized to the core mass, and the B-H loop data were obtained at 1, 5, 10, 20, and 50 kHz. For each frequency, the data was taken at 23 C and then in increments of 50 C to 300 C. The data was again taken at 23 C after the material's exposure to 300 C.

EXPERIMENTAL RESULTS

The experimental results for the OG and NOG 50Ni-50Fe and Metglas 2605SC materials are given in Figures 1 through 10. The data are for a single core and are representative of the results obtained for the three test cores of each material.

The decrease in saturation flux density (B_{Sat}) with temperature for each material is shown in Figure 1. At 23 C the OG 50Ni-50Fe has the highest B_{Sat} of about 1.6 T, the Metglas 2605SC has slightly lower B_{Sat}, and the NOG 50Ni-50Fe has the lowest B_{Sat} of about 1.4 T. The materials retain this order from 23 to 300 C. At 300 C the B_{Sat} of the OG 50Ni-50Fe has decreased to about 1.1 T, but now both the Metglas 2605SC and NOG 50Ni-50Fe have decreased to about the same B_{Sat} value of 0.96 T.

The SCL as a function of B_m with f as the parameter is given for the OG and NOG 50Ni-50Fe and Metglas 2605SC materials in Figures 2, 5, and 8 respectively. The (a)-figures are for 23 C and the (b)-figures are for 300 C. These plots show that each material exhibits the following characteristics: For a given f, log-log plots of the SCL increase nearly linearly with B_m; for a given B_m, the SCL increases as f increases; and for a given B_m and f, the SCL at 300 C is considerably lower than at 23 C.

Figures 3, 6, and 9 give more detail on how the SCL for these materials changes between 23 and 300 C. Here the (a)-set of figures is for B_m = 1.0 T and the (b)-set is for B_m = 0.3 T. These figures show that for a given f, all the materials have decreasing SCL over the entire temperature range, except that the Metglas 2605SC curves for 5, 10, and 20 kHz have a small increase in SCL between 23 and 50 C.

A representation of the dynamic B-H loops at selected frequencies for each of the three materials is shown in Figures 4, 7, and 10. The (a)-figures are for 23 C and the (b)-figures are for 300 C. To enable valid comparisons, each of the B-H loops is drawn for the same B_m of 0.9 T. Comparison of the 23 C with the 300 C loops for the same frequency, clearly shows the decrease in loop area at 300 C; this area represents the core loss per unit volume.

MATERIALS COMPARISON

A comparison of different soft magnetic materials in terms of SCL is valid only if each material has the same physical density; otherwise, the core loss must be the basis for comparison. The 50Ni-50Fe alloys have the same density and so their SCLs can be compared. A comparison of Metglas 2605SC with the two 50Ni-50Fe alloys must be done on a core loss basis because Metglas 2605SC has a considerably lower density.

Table 2 compares the core loss of the three materials, assuming that each core has the same A_c and $\bar{\ell}_m$, and hence also the same volume. This implies that the ratio of the core masses equals the ratio of the material's densities. If the OG and NOG 50Ni-50Fe cores each weigh 1 lb., then the Metglas 2605SC core weighs 0.887 lbs. A comparison of the core losses for a given T, f, and B_m in Table 2 shows that the NOG 50Ni-50Fe alloy has the lowest losses in the majority of the cases. In the other cases, it has the second lowest loss. Thus, in most instances, the NOG 50Ni-50Fe would tend to be the material selected from core loss considerations. At 23 C and all frequencies listed, the Metglas 2605SC material needs to be considered because it has a core loss very comparable to that for the NOG 50Ni-50Fe alloy. At 150 and 300 C and for the frequencies of 20 and 50 kHz, the OG 50Ni-50Fe alloy should be considered because it has a core loss comparable to that of the NOG 50Ni-50Fe alloy.

CONCLUSION

The experimental results for the soft magnetic materials given in this paper should enable the magnetics designer to make better decisions in the application of these materials in the temperature range of 23 to 300 C and frequency range of 1 to 50 kHz. The results in Table 2 show that the NOG 50Ni-50Fe alloy has either the lowest or next lowest core loss, so that the tendency would be to select this material. Finally, it should be noted that the experimental data presented here was obtained under very short-term temperature exposure and thus, long-term temperature exposure must be investigated to determine if ageing affects the results.

ACKNOWLEDGMENT

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[6] Fritz, J.F. and Clark, J.J., "Effects of Temperature on Magnetic Properties of Nickel-Iron Alloys Over Temperature Range -60 to 250 C," Electrical Manufacturing, November 1958.

[7] Frost, R.M., McVay, R.E. and Pavlovic, D.M., "Evaluation of Magnetic Materials for Static Inverters and Converters," NASA Contractor Report 1226, February 1969.

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Table 1. Comparison of oriented and nonoriented - grain, 50 Ni-50 Fe and Metglas 2605SC properties.			
Property	50 Ni - 50 Fe Oriented - Grain	50 Ni - 50 Fe Nonoriented - Grain	Metglas 2605 SC
Composition	50% Ni, 50% Fe (1)	50% Ni, 50% F, (1)	$Fe_{81}B_{13.5}Si_{3.5}C_2$ (1)
Structure	Crystalline	Crystalline	Amorphous
Saturation Induction	1.42 - 1.58 T (1)	1.15 - 1.40 T (1)	1.61 T (2)
Resistivity	45×10^{-6} ohm -cm (1)	45×10^{-6} ohm -cm (1)	135×10^{-6} ohm -cm (2)
Curie Temperature	500 C (1)	500 C (1)	370 C (2)
Crystallization Temp.	—	—	480 C (2)
Melting Point	1425 C (1)	1425 C (1)	1100 C (2)
Thermal Conductivity	13 w/m C (4)	13 w/m C (4)	9 w/m C (2)
Density	8.25 g/cm 3 (3)	8.25 g/cm 3 (3)	7.32 g/cm 3 (2)

(1) Magnetics TWC - 300 T, Design Manual Featuring Tape Wound Cores.
(2) Allied Metglas Products, Metglas Magnetic Alloys.
(3) The Arnold Engineering Company, TC - 101 E, Tape Wound Cores.
(4) Carpenter, Soft Magnetic Alloys, Electronic Alloys, 11 - 88.

Table 2. Comparison of core less of nonoriented and oriented - grain 50 Ni - 50 Fe and Metglas 2605 SC for cores having the same Ac and ℓm with the nonoriented - grain 50 Ni - 50 Fe core weight set equal to 1 lb.

		Core Loss (w)								
		50 Ni - 50 Fe Nonoriented - Grain			50 Ni - 50 Fe Oriented - Grain			Metglas 2605 SC		
f (kHz)	B_m (T)	23 C	150 C	300 C	23 C	150 C	300 C	23 C	150 C	300 C
1	.6	1.2	.80	.43	2.5	1.5	1.0	1.2	1.0	.60
1	.9	2.3	1.5	.86	4.1	2.6	2.0	2.4	1.8	1.2
1	1.2	3.6	2.4	-	5.9	3.9	-	3.9	2.8	-
5	.6	13	8.6	4.4	18	11	6.6	13	11	6.2
5	.9	24	15	8.7	30	19	13	25	19	12
5	1.2	36	24	-	42	28	-	38	28	-
10	.6	37	24	12	44	26	16	37	32	17
10	.9	64	43	25	73	47	32	66	53	32
10	1.2	96	66	-	103	70	-	99	79	-
20	.3	39	26	11	46	25	11	36	33	16
20	.6	101	69	37	108	66	41	94	80	42
50	.1	29	19	6.0	38	16	4.3	29	25	11
50	.3	151	106	48	147	88	42	151	122	63

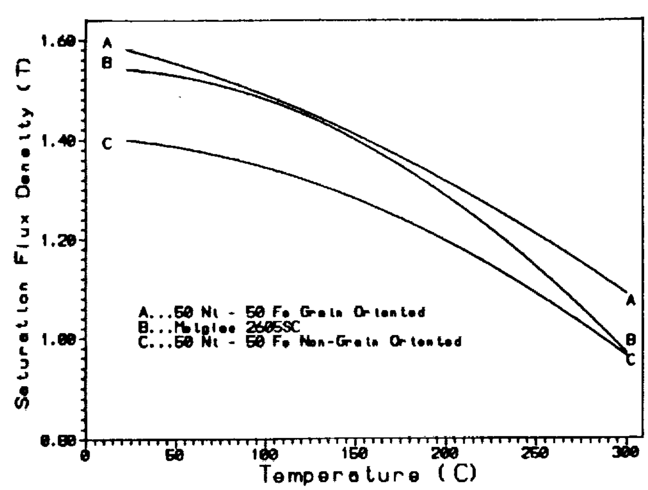
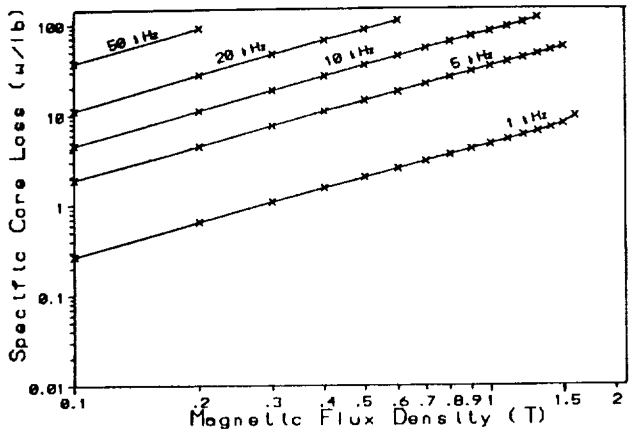
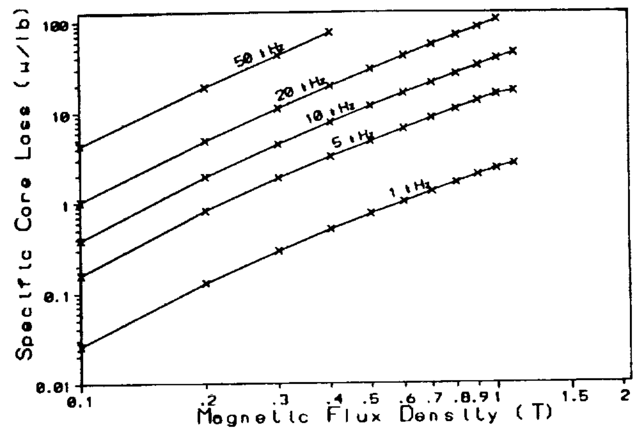


Figure 1. Saturation flux density, B_{sat}, versus temperature. B_{sat} taken from B-H saturation loops at 1 kHz.

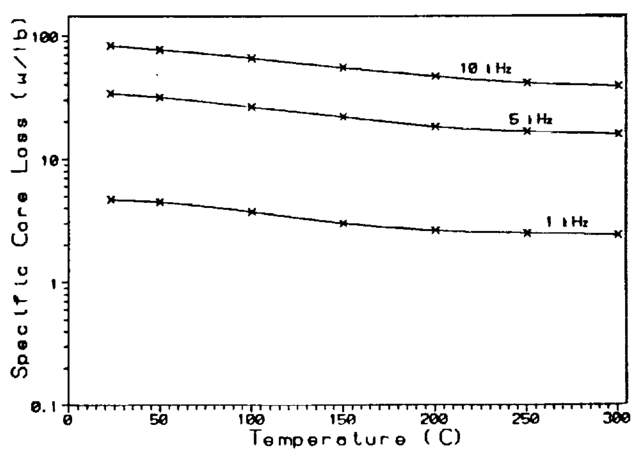


(a)



(b)

Figure 2. Oriented - grain 50 Ni-50 Fe specific core loss versus magnetic flux density at selected frequencies (sinewave voltage excitation) for toroid wound from 0.001 inch thick tape (1A-01). (a) T=23 C, (b) T=300 C.



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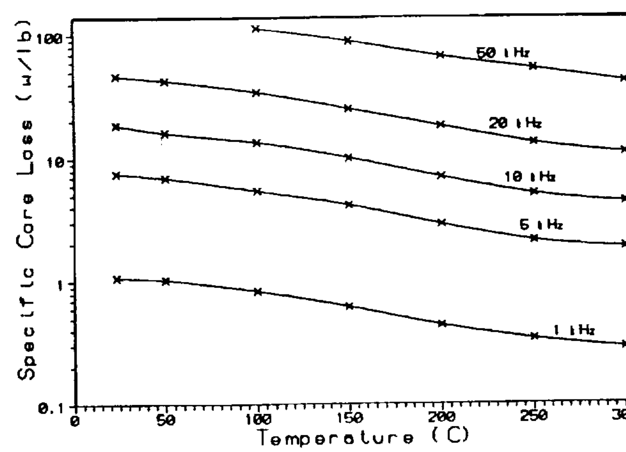
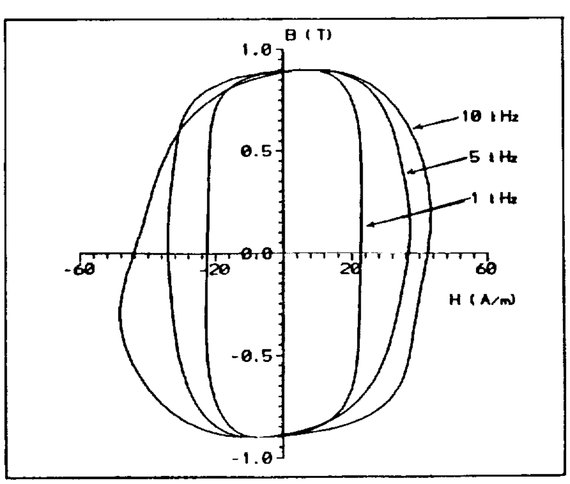
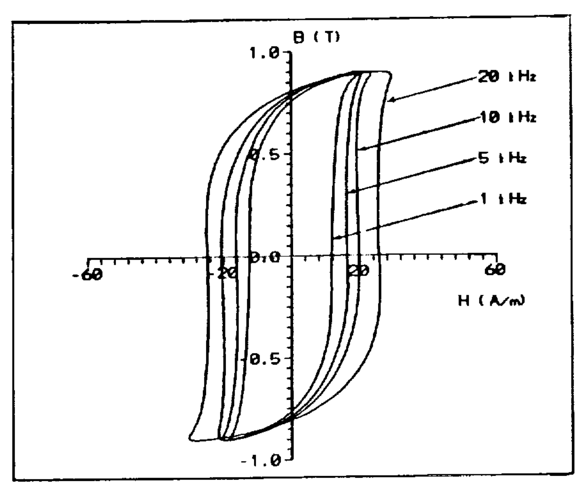


(b)

Figure 3. Oriented - grain 50 Ni - 50 Fe specific core loss versus temperature at selected frequencies (sinewave voltage excitation) for toroid wound from 0.001 inch thick tape (1A-01). (a) Bm = 1.0 T, (b) Bm = 0.3 T.

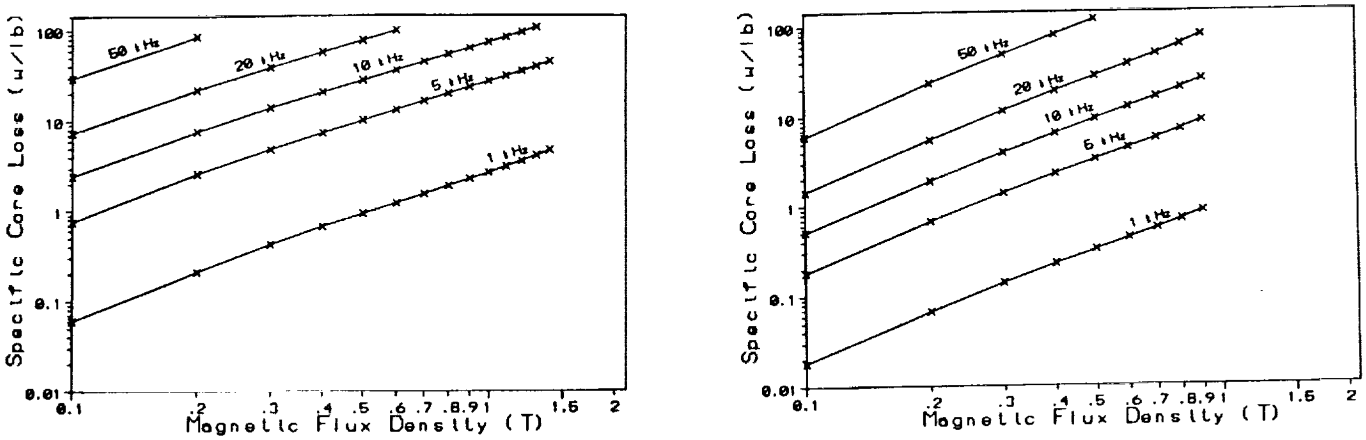


(a)



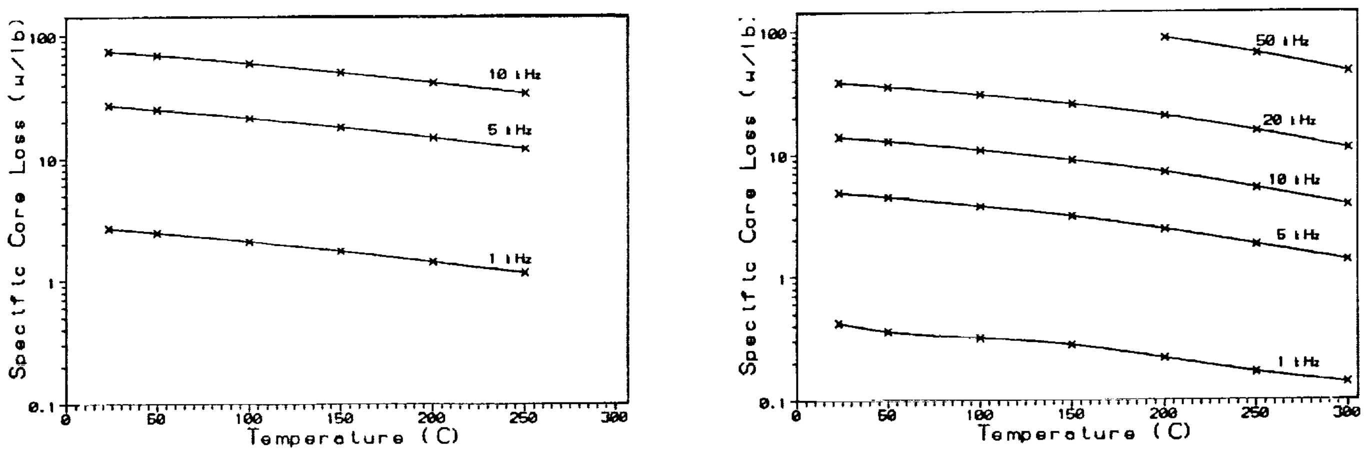
(b)

Figure 4. Oriented - grain 50 Ni - 50 Fe B-H loops for Bm = 0.9 T at selected frequencies (sinewave voltage excitation) for toroid wound from 0.001 inch thick tape (1A - 01). (a) T=23 C, (b) T=300 C.



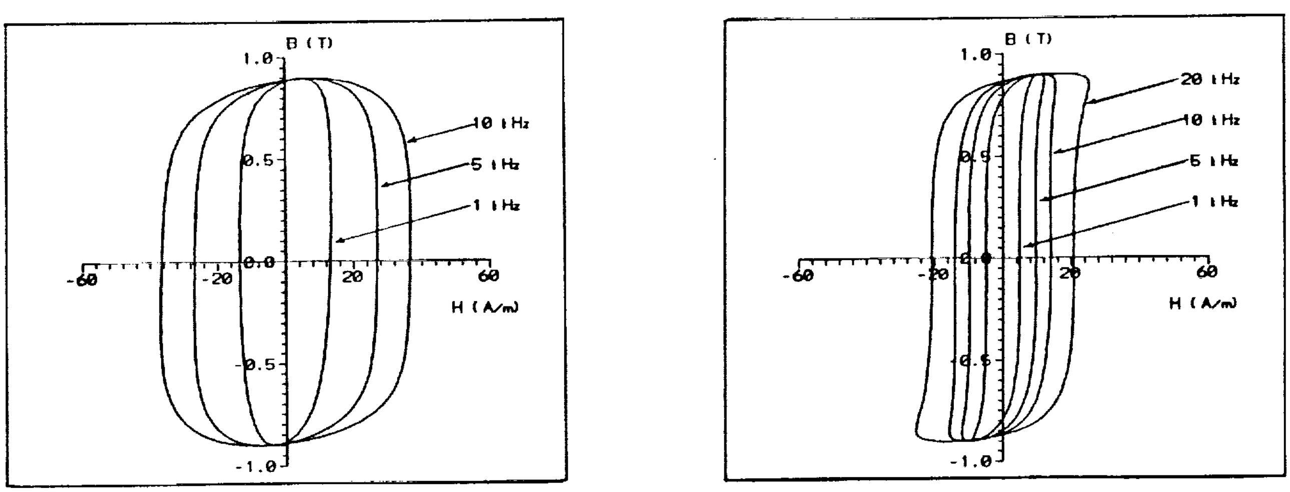
(a) (b)

Figure 5. Nonoriented - grain 50 Ni - 50 Fe specific core loss versus magnetic flux density at selected frequencies (sinewave voltage excitation) for toroid wound from 0.001 inch thick tape (1H-20). (a) T=23 C, (b) T=300 C.



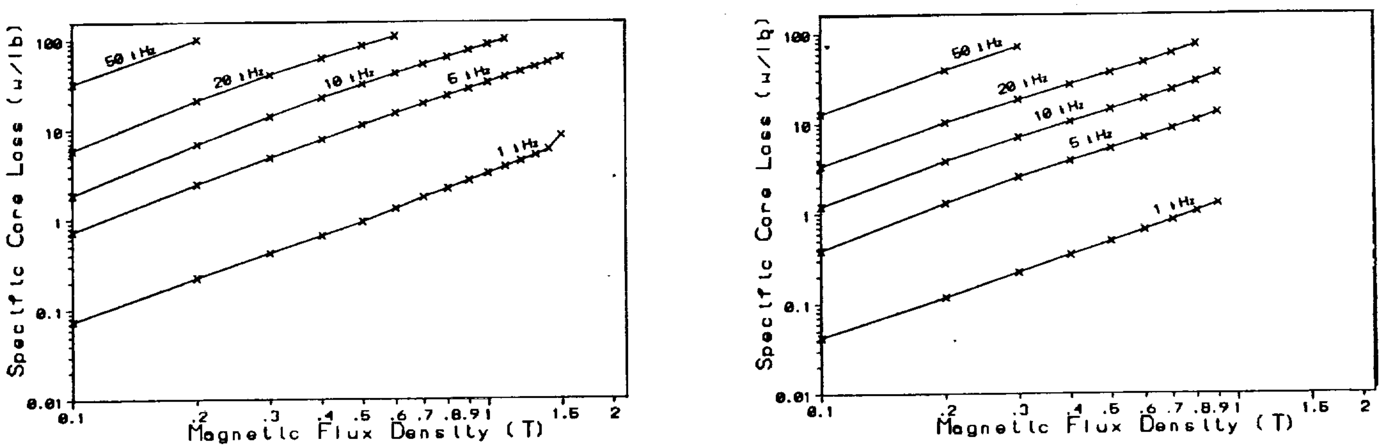
(a) (b)

Figure 6. Nonoriented - grain 50 Ni - 50 Fe specific core loss versus temperature at selected frequencies (sinewave voltage excitation) for toroid wound from 0.001 inch thick tape (1H-20). (a) Bm = 1.01 T, (b) Bm = 0.3 T.



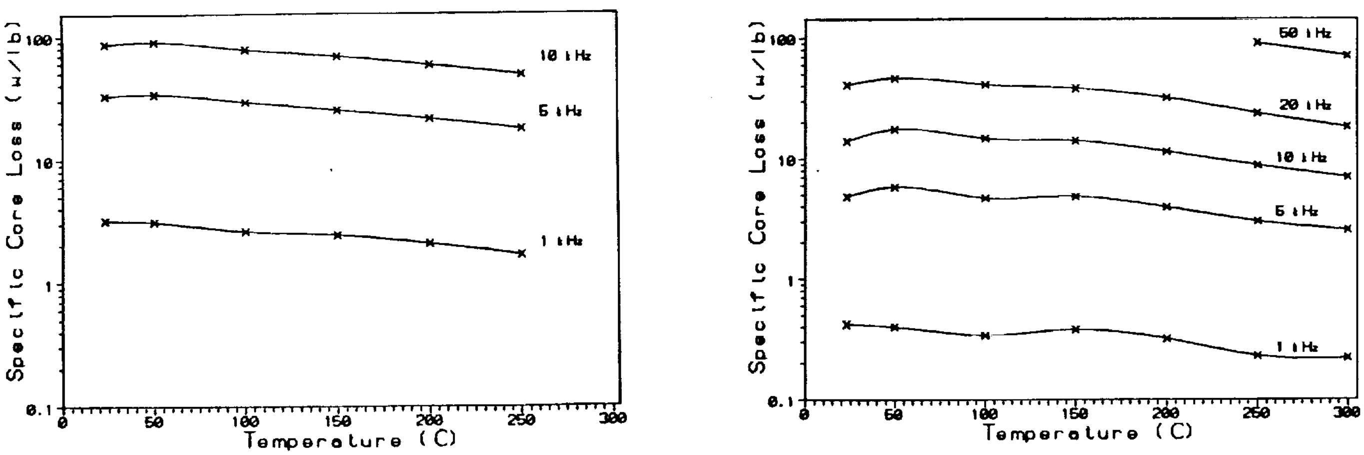
(a) (b)

Figure 7. Nonoriented - grain 50 Ni - 50 Fe B-H loops for Bm = 0.9 T at selected frequencies (sinewave voltage excitation) for toroid wound from 0.001 inch thick tape (1H-20). (a) T=23 C (b) T=300 C.



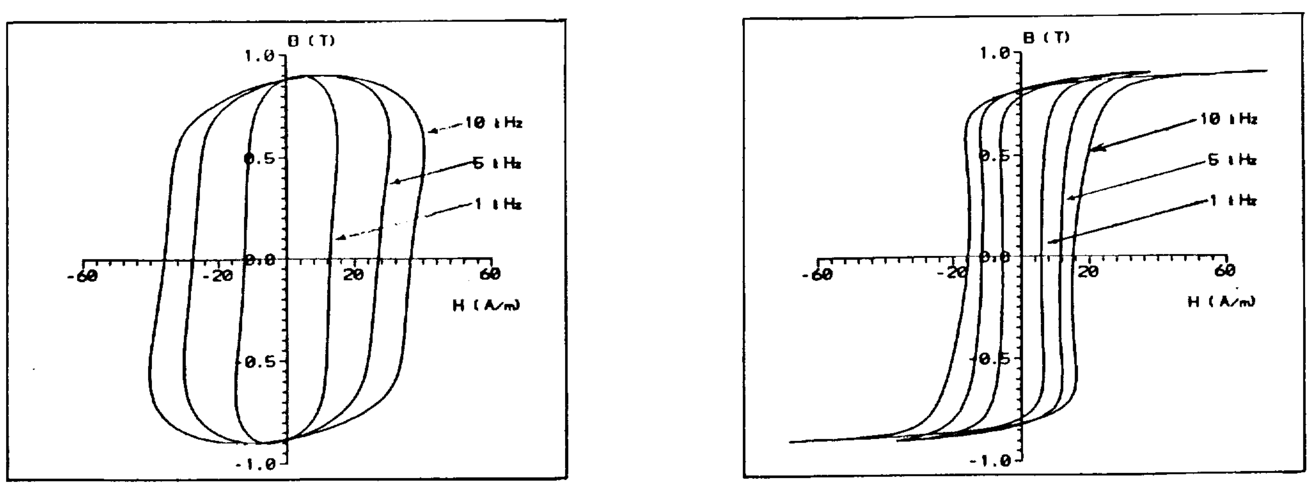
(a) (b)

Figure 8. Metglas 2605SC specific core loss versus magnetic flux density at selected frequencies (sinewave voltage excitation) for toroid wound from 0.001 thick tape (1B-03). (a) T=23 C (b) T=300 C.



(a) (b)

Figure 9. Metglas 2605SC specific core loss versus magnetic flux density at selected frequencies (sinewave voltage excitation) for toroid wound from 0.001 inch thick tape (1B-03). Bm = 1.0 T, (b) Bm = 0.3 T.



(a) (b)

Figure 10. Metglas 2605SC B-H loops for Bm = 0.9 T at selected frequencies (sinewave voltage excitation) for toroid wound from 0.001 inch thick tape (1B-03). (a) T=23 C, (b) T=300 C.

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